Permeability as function rock mechanical behaviour

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Effect of pressure on permeability is analyzed using phenomenological models. Analytical algorithms which compose a coherence unit, are presented to estimate the rock permeability, consequently the well capacity in case of rigid (incompressible), elastic, elastic-viscous, elastic-plastic and elastic - plastic - viscous rocks. The algorithms can be used for estimation of porosity-pressure functions also. An example is presented to show the application of the recommended methods. Without understanding the effect of stress on the permeability in case of low permeability and porosity reservoirs, the well production can not be predicted. The analysis proves that the research has to continue for HT and HP reservoirs to reveal the relation between rock parameters and pressure (temperature) load for rocks having complex mechanical behaviour.

Key words: permeability, porosity, analytical algorithms, well capacity

Introduction

In special cases - HP, HT and low porosity rocks - due to pressure (temperature) load permeability (and porosity) may change influencing the efficiency of recovery technology. This process is very complicated and sophisticated this is why to understand the rock mechanical behaviour as function of pressure very simple material equations are recommended.

There are a number of material equations, the general form of them is as follows:

$$g(\sigma,\varepsilon,\dot{\sigma},\dot{\varepsilon},\tau) = 0$$

where:

g - general symbol of functional relation,

σ - pressure (normal stress) load,

$\dot{\sigma}$ - derivative of stress as function of time,

ε - specific strain,

$\dot{\varepsilon}$ - derivative of specific strain as function of time,

τ - time.

Solution of this material equation is very complicated, therefore in the practice generally approximation solution is used- Kaliszky S.[6]

The specific (e.g. linear) strain (ε) is calculated in the following manner - Kaliszky S.[6] - using the superposition principle:

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_\nu$$

and

$$\sigma = \sigma_e + \sigma_p + \sigma_\nu$$

Index - (e) elastic, (p) plastic and (ν) viscous component

The rock properties (e.g. permeability , porosity etc) depend on the volumetric strain, but the volumetric strain is proportional with the linear strain, therefore our analysis is based on the linear strain laws with some modifications.

For example the permeability change (Δk) due to pressure (and/or temperature) load approximately is as follows:

$$\Delta k = \Delta k_e + \Delta k_p + \Delta k_\nu$$

Because $\Delta k_\nu = \Delta k_\nu(\tau)$, then $\Delta k = \Delta k(\tau)$, that is time dependent.

In the following part we accept this principle to understand the unusual behaviour of these rocks comparing with the conventional ($\Delta k = 0$) reservoir rock's material.

Long ago the researchers recognized the unusual behaviour of some rocks due to pressure load but in the reservoir engineering practice this has been neglected.

Research with respect to permeability as function of pressure has commenced at 1956-57 in the former Soviet Union in case of Groznyenszkij Field - Majdebor V.N.[11] Kuszakov M.M.,Gudok N.Sz.[7] showed with laboratory measurements that cycling pressure load results a permanent permeability reduction. Abgrall E.[1] has got the same result respect to porosity and permeability measurements. He demonstrated the hysteresis of these parameters including the residual change of them. Matveev I.M. (1965) - after Kotjahov F.I.[9] - proved with field tests that in case of Malgobek-Voznyeszenko reservoir, the cycling load of a well (production-injection) the productivity index is not constant, there is a hysteresis. After 2.5 months difference in productivity index was diminished. Some of the laboratory measurements proved that after a given time the residual change of the permeability disappears: Thomas R.D.,Ward D.C.[13] or Aggour M.A., Mallk S.A., Hararl Z.Y.[2] For example Thomas R.D.,Ward D.C.[13] have observed that the residual change of permeability due to hysteresis disappeared after 3-6 weeks and the cores recovered their original permeability. This time could be shortened by storing the cores in an oven at 70 °C.

Aggour M.A., Mallk S.A., Hararl Z.Y.[2] studied the effect of cyclic pressure load on permeability.

Chen S., Li H., Zhang Q., Yang D.[4] presented a capacity equation of a oil well (L-6) of Qinszi Oilfield (China) which has not been a classical (monotonic) one against the depression (pressure load).

The data are as follows:

Δp (bar)*	0	85	100	140	155	210	340	510
Rate (m^3/d)*	0	120	130	147	148	140	120	35

note* : data is read from the presented table

Δp_{opt} - 180 bar; q_{max} - 150 m^3/d

The other data: pay-zone depth 4 000 - 5 000 m (13 123 - 16 404 ft), fractured rock (dolomite, dolomite mudstone and gompholite), matrix permeability 0.45-3.16 mD , fracture permeability (100 mD), under-saturated oil, oil viscosity (5.73 cP). During the measurements the stabilization time was 3-5 days/ choke 4.5 - 8 mm, (11.3/64 - 20.2/64 in.).

In the following, using phenomenological analysis, we try to understand the already explained unusual behaviour of reservoir rocks with complex mechanical properties assuming isotherm processes. In the our analysis the rock damage is not considered. The recommended algorithms could be applied for calculation the porosity-pressure relation also. We explain them for only production pressure load, for injection we can used them also.

1. Incompressible (rigid) reservoir rock

The rock is incompressible, consequently the permeability (k) is constant. In this case e.g. a well discharge is calculated using the well known Dupuit equation:

$$q = \frac{2\pi hk}{\mu B}\frac{1}{s+\ln\frac{r_2}{r_1}}(p_2-p_1) \tag{1}$$

where:

- q oil rate
- h pay effective thickness
- k permeability
- μ viscosity
- B volume factor
- p_2 pressure at outer drainage radius (r_2)
- p_1 pressure at well radius (r_1)
- s skin factor

2. Elastic reservoir rock

2.1. Elastic reservoir rock with no transient component (non viscous rock)

In this case it is assumed:

$$k(p) = k_0 e^{-\alpha(p_2-p)} \tag{2}$$

where:

- $k(p)$ pressure dependent permeability
- k_0 reference permeability (at p_2 pressure)
- α compressibility factor of permeability (mD/mD · 1/bar)

Based on this equation Gorbunov A.T.[5] formula is as follows:

$$q = \frac{2\pi hk}{\mu B}\frac{1}{s+\ln\frac{r_2}{r_1}}\left[\frac{1-e^{-\alpha(p_2-p_1)}}{\alpha}\right] \tag{3}$$

Pápay J. (2009) generalized Gorbunov's formula in the following way :

$$q = \frac{2\pi hk}{\mu B}\frac{1}{s+\ln\frac{r_2}{r_1}}e^{-ic_e p_0}\left[\frac{e^{-ic_e p_2}-e^{-ic_e p_1}}{ic_e}\right] \tag{4}$$

where:

- p_0 reference pressure at which the reference permeability determined
- i pore structure coefficient :
  - if the rock is inter-particle porosity one, then i=2;
  - if the rock is fracture porosity one, then i=3;
- c_e isotherm effective compressibility factor of porosity

If k_0=k=k_2, the p_0=p_2 and $ic_e=\alpha$ then Equation (4) reduces into Equation (3) or if α=0 then we are getting Equation (1). In case of Equation (1), (2) and (3) the q=$q(\Delta p)$ functions are monotonic ones.

Chen S., Li H., Zhang Q., Yang D.[4] recommended the following equation to get a capacity equation having maximum production (q_{max}) at a Δp value (Δp_{opt}):

according to their laboratory measurements - α - linear function of pressure load, that is a and b = const.

$$\alpha = a(p_2-p_1)+b \tag{5}$$

$\Delta p = p_2$-p_1;

The recommended form of the compressibility parameter - Equation (5) - can be substituted both in Equation (3) and (4).

Figure - 1. demonstrates different types of capacity equations if the flow is laminar and the rock is rigid (line-1) or elastic (line-2 or 3). In this case of line-3 the capacity equation is not a monotonic one. In the discussed cases there is no hysteresis due to cyclic pressure load.

In the following points only the permeability change is discussed (porosity could analyzed in similar way). Well

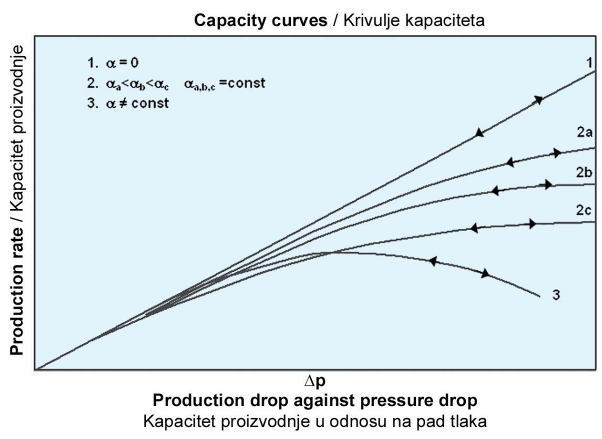

Fig.1 Production rate against pressure drop
Sl. 1. Kapacitet proizvodnje u odnosu na pad tlaka

discharged, which is based on permeability-pressure function is excluded in the following points due to complicated relations. If the permeability change is known due to pressure load then numerical model should be used or geometrical average permeability recommended for calculation of the well discharge etc.

2.2. Elastic reservoir rock with transient component (viscous rock)

According to Kotjahov F.I.[9] the specific linear strain (ε_e) for elastic rock can be divided into two components: instant (ε_{1e}) and transient (ε_{2e}).

$$\varepsilon_e = \varepsilon_{1e} + \varepsilon_{2e} \tag{6}$$

The transient component according to Kotjahov F.I.[9] or according to Kaliszky S.[6] is as follows:

$$\varepsilon_{2e} = \varepsilon_{2e0}\left(1 - e^{-\frac{E}{\nu}\tau}\right) \tag{7}$$

where:

- E elasticity modulus
- ν rock viscosity which may depend on shearing velocity
- τ time
- ε_{2e0} specific strain if duration of load is infinite

Both permeability and porosity is proportional with the volumetric deformation. The latter is proportional with the linear deformation, so porosity and permeability may depend on time e.g. exponentially.

Accepting this principle, due to pressure load the elastic change of permeability (porosity) is as follows:

$$\Delta k_e = \Delta k_{e1} + \Delta k_{e2} \tag{8}$$

where:

- Δk_{e1} instant change of permeability
- Δk_{e2} time dependent change of permeability

Calculation these changes the following formulas are recommended:

$$\Delta k_{e1} = l k_0\left(1 - e^{-\alpha\Delta p}\right) \tag{9a}$$

and

$$\Delta k_{e2} = (1-l)k_0\left(1 - e^{-\lambda\tau}\right)\left(1 - e^{-\alpha\Delta p}\right) \tag{9b}$$

It means that viscous component is time dependent.

where:

- l fraction of the instant change of permeability to the total one (if the time were infinite)
- k_0 reference permeability (e.g. at p_0 original pressure which is reference one)
- $\Delta p = p_0 - p$
- α specific permeability (porosity) change due to unit pressure change (mD/mD *1/bar)
- λ rate of convergence to get the final permeability (1/day or 1/month)
- τ time (day or month)

If the time is infinite (or long enough), then:

$$\Delta k_e = k_0\left(1 - e^{-\alpha\Delta p}\right) \tag{10}$$

This model corresponds to Kelvin -Voight rock mechanical model.

If the pressure load changes as function of time the following calculation process is recommended:

Time step	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	………	$\Delta\tau_n$
p_0-pi change of pressure	Δp_1	Δp_2	Δp_3	………	Δp_n
Δp for calculation	$(p_0-p_1)/2$	$(p_0-p_2)/2$	$(p_0-p_3)/2$	………	$(p_{n-2}-p_n)/2$

The time is as follows: $\tau = \sum \Delta\tau_i$; for simplicity: $\Delta\tau_1 = \Delta\tau_2 = \Delta\tau_3 = \Delta\tau_4 =$ ----- $= \Delta\tau$

The change of permeability is calculated as function of time step.

At the end of the **first time step** the change of permeability is as follows:

$$\Delta k_{e1} = l k_0\left(1 - e^{-\alpha\Delta p_1}\right)$$

$$\Delta k_{e2} = (1-l)k0\left(1 - e^{-\lambda\Delta\tau}\right)\left(1 - e^{-\alpha\Delta p_1}\right)$$

and

$$\Delta k_e = \Delta k_{e1} + \Delta k_{e2}\big|_1 \tag{11. a}$$

At the end of the **second time step** the change of permeability is as follows:

$$\Delta k_{e1} = l k_0\left(1 - e^{-\alpha(\Delta p_1 - \Delta p_2)}\right)$$

$$\Delta k_{e2} = (1-l)k_0\left\{\left(1 - e^{-2\lambda\Delta\tau}\right)\left(1 - e^{-\alpha\Delta p_1}\right) + \left(1 - e^{-\lambda\Delta\tau}\right)\left[e^{-\alpha\Delta p_1} - e^{-\alpha(\Delta p_1 + \Delta p_2)}\right]\right\}$$

and

$$\Delta k_e = \Delta k_{e1} + \Delta k_{e2}\big|_2 \tag{11. b}$$

At the end of the **n-th time step** the change of permeability is as follows:

$$\Delta k_{e1} = l\, k_0\left(1 - e^{-\alpha\sum_{i\,1}^{n}\Delta p_i}\right)$$

$$\Delta k_{e2} = (1-l)k_0\left\{\left(1 - e^{-n\lambda\Delta\tau}\right)\left(1 - e^{-\alpha\Delta p_1}\right) + \left(1 - e^{-(n-1)\lambda\Delta\tau}\right)\left[1 - e^{-\alpha\Delta p_1} - e^{-\alpha\sum_{i\,1}^{n}\Delta p_i}\right] + \right\}$$
$$\left(1 - e^{-(n-2)\lambda\Delta\tau}\right)\left[e^{-\alpha\sum_{i\,1}^{2}\Delta p_i} - e^{-\alpha\sum_{i\,1}^{3}\Delta p_i}\right] + \ldots\ldots + \left(1 - e^{-\lambda\Delta\tau}\right)\left[e^{-\alpha\sum_{i\,1}^{n-1}\Delta p_i} - e^{-\alpha\sum_{i\,1}^{n}\Delta p_i}\right]$$

and

$$\Delta k_e = \Delta k_{e1} + \Delta k_{e2}\big|_n \tag{11. c}$$

3. Elastic-plastic reservoir rock

Two models are presented and the coherence between them is also shown. The physical meaning of them is demonstrated on Figure 2.

Figure 2a. shows the permeability against the pressure in case of elastic reservoir rock with no viscous component. If Δp increases then the permeability decreases along the line of 012. If Δp decreases then the permeability increase along the line of 210. There is no permeability hysteresis.

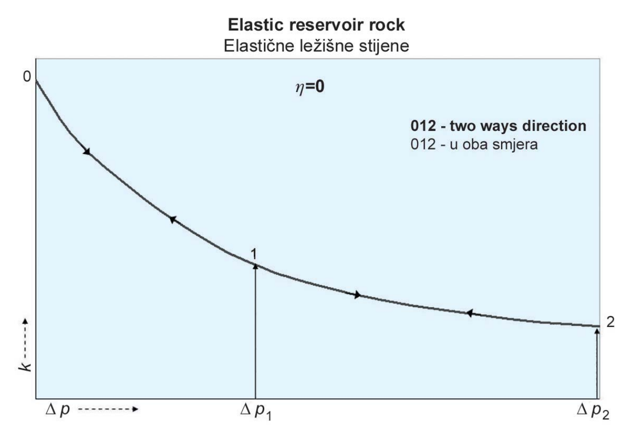

Fig. 2a. Permeability against the pressure
Sl. 2a. Ovisnost propusnosti o tlaku

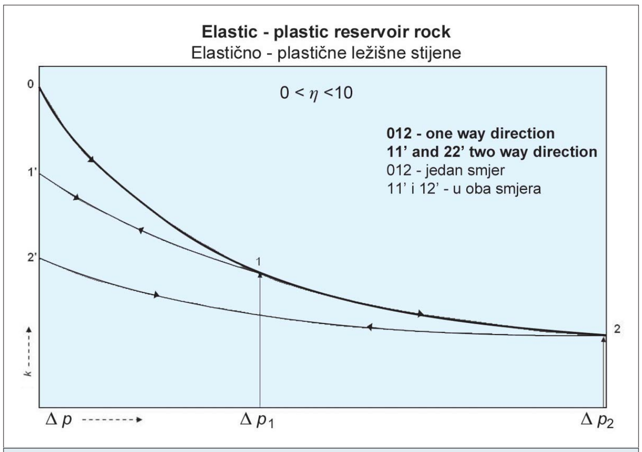

Fig. 2c. Permeability against the pressure
Sl. 2.c. Ovisnost propusnosti o tlaku

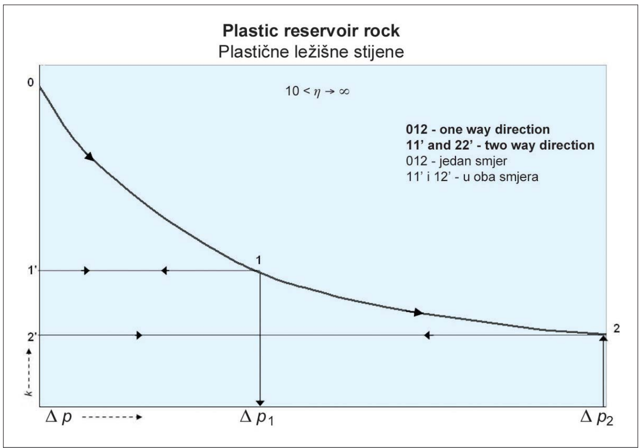

Fig. 2b. Permeability against the pressure
Sl. 2b. Ovisnost propusnosti o tlaku

Figure 2b. shows the permeability against the pressure in case of plastic reservoir rock. In this case the elasticity coefficient is : $\eta>10$ (e.g. Gorbunov A.T.-1981 model).

If Δp increases then the permeability decreases along the line of 012. If $\Delta p=\Delta p_1$ then the permeability is k_1. If Δp decreases ($\Delta p\rightarrow 0$) then the permeability remains constant ($k=k_1=k'_1$). If Δp increases again ($\Delta p\rightarrow\Delta p_1$) then the permeability remains constant ($k=k_1=k'_1$). If Δp grater then Δp_1 ($\Delta p>\Delta p_1$) the permeability decreases along the line of 12. If $\Delta p=\Delta p_2$ then the permeability is k_2. If Δp decreases again ($\Delta p\rightarrow 0$) then the permeability remains constant ($k=k_2=k'_2$) etc. It means that we never can go back to k_0, there is permeability hysteresis, consequently there is production rate hysteresis also.

Figure 2c. shows the permeability against the pressure in case of elastic-plastic reservoir rock. In this case the elasticity coefficient is: $0<\eta<10$ (e.g. Gorbunov A.T.-1981 model).

If Δp increases then the permeability decreases along the line of 012. If $\Delta p=\Delta p_1$ then the permeability is k_1. If Δp decreases ($\Delta p\rightarrow 0$) then the permeability increases slightly ($k>k_1$; $k_{max}=k'_1$). If Δp increases again ($\Delta p\rightarrow\Delta p_1$) then the permeability decreases slightly along the line 1'1 ($k<k'_1$; $k_{min}=k_1$). If Δp grater then ($\Delta p>\Delta p_1$) the permeability decreases along the line of 12. If $\Delta p=\Delta p_2$ then the permeability is k_2. If Δp decreases again ($\Delta p\rightarrow\Delta p_2$) then the permeability increases slightly along the line 22' ($k>k_2$; $k_{max}=k'_2$). If Δp increases again ($\Delta p\rightarrow\Delta p_2$) then the permeability decreases slightly ($k<k'_2$; $k_{min}=k_2$) on the same line. It means that we never can go back to k_0, there is permeability hysteresis, consequently there is production rate hysteresis also.

Described processes can be simulated with two analytical models which are presented.

Models based on the following principles:

- $k=k(\Delta p)$ function is hyperbolic (Model-I) or exponential (Model-II) type;
- there is two type of curves (Figure - 2b or 2c), 012 the main curve, and the subordinate curves (11' or 22'). Both function types (main curve and subordinate ones) are same type functions (hyperbolic or exponential), but the slops of them are different. The main curve' slop is larger then subordinates' ones. The later is different from each other if the reservoir rock is elastic-plastic, if the rock is plastic then slops of the subordinate curves are zero;
- in the points of intersections the actual permeability is same for both type of curves;
- the k_1' or k_2' is calculated ($\Delta p=0$) with help of intersection permeability (k_1 or k_2) and with slop (or parameter) of subordinate functions according to a given algorithm;
- change of permeability is instantaneous.

Model - I. is the process of Barenblatt G.I.[3], (Equation -12a) and Korotaev Ju.P., Gerov L.G., Zakirov Sz.N., Scserbakov G.A.[10], (Equation -12b) who recommended hyperbolic functions (power equations) to calculate the permeability against the pressure load.

$$k=k_0\left(\frac{p}{p_0}\right)^{\alpha^*} \quad \text{main curve equation} \qquad (12.a)$$

$$\alpha_i^* = \alpha^* \left(\frac{p_i}{p_0}\right)^{\eta^*} \quad \text{subordinate curves' parameters} \qquad (12.b)$$

Model - II. is the process of Gorbunov A.T.[5], (Equation -13a and 13 b.) who used exponential functions (e.g. Equation 2) instead of hyperbolic ones:

$$k = k_0 e^{-\alpha(p_0-p)} \quad \text{main curve equation} \qquad (13.a)$$

$$\alpha_i = \alpha e^{-\eta(p_0-p_i)} \quad \text{subordinate curves' parameters} \qquad (13.b)$$

The coherence between the two models is as follows:

$$\alpha = \alpha^* \frac{2.3}{p_0 - p} \log\frac{p_0}{p} \qquad (14.a)$$

$$\eta = \eta^* \frac{2.3}{p_0 - p} \log\frac{p_0}{p} \qquad (14.b)$$

If the p>0.4p_0 the two model give similar result.

In the Equations (12) and (13) the parameters are:

- k_0 reference permeability (at original reservoir pressure: p_0),
- k actual permeability (at actual reservoir pressure: p),
- α, α^* compressibility coefficients referring the permeability, as if rock would be completely elastic,
- α_i, α_i^* compressibility coefficients referring the permeability, considering elasticity-plasticity rock behaviour ($\alpha > \alpha_i$ and $\alpha^* > \alpha_i^*$)
- η, η^* plasticity coefficients if :
  - $\eta = 0$ the reservoir rock is elastic
  - $0 < \eta < 10$ the rock is elastic-plastic
  - $\eta > 10$ the rock is plastic[5]

Both models consider instantaneous permeability change for elastic-plastic reservoir rock.

4. Elastic-plastic-viscous reservoir rock

The rock texture may be very combined, consequently the material equation is very complex one. In the practice the solution of material equation very often takes place with approximation and with simplification. For exact solution numerical models are recommended considering fluids' flow and rock mechanical behaviour. These models are called as coupled geo-mechanical models which on late years more often are recommended and used in the practice.

We suggest the following algorithm to estimate the change of permeability using superposition principle.

$$\Delta k_p = \eta^{**}(\Delta k_e + \Delta k_v)_{max} \qquad (15)$$

note: till a point of the time the maximum change of permeability - $(\Delta k_e + \Delta k_v)_{max}$ - is considered which is occurred during this period

where:

plasticity coefficient ($\eta^{**} <= 1$), which can be constant or load (pressure) dependent (e.g. exponential).

$$\eta^{**} = \eta_0^{**} e^{-c_\eta \Delta p_{max}} \qquad (16)$$

where:

- η_0^{**} reference elastic coefficient
- c_η elasticity parameter (e.g. $c_\eta = 0$)
- Δp_{max} max pressure load during the time interval

Start of time interval is always $\tau = 0$, its end is the actual time: τ.

$$\Delta p_{max} = [p_0(\tau = 0) - p(\tau)]_{max}$$

The time dependent total change of permeability is as follows:

$$\Delta k(\tau) = \Delta k_e + \Delta k_v(\tau) + \Delta k_p \qquad (17)$$

$(\Delta k_e + \Delta k_v)$ is calculated according to point 2.

Value of Δk_p never decreases, only increases or constant. For example if from a time point pressure load decreases Δk_p remains at its maximum value which was before. At plastic process the permeability never regenerates, never gets back its original value.

Example

Initial reservoir pressure is 200 bar (2 900 psi) at $\tau = 0$, then the pressure drops instantaneously with Δp=bar. During three month the pressure is 100 bar (1 450 psi), then the pressure instantaneously increases back to the original value. Duration of the total interval is 6 month. It has to calculate the change of permeability as function of time if the original permeability is 100 mD, and assuming different rock mechanical properties. Solutions are presented in the table 1.

Summary

- On a coherence base algorithms were developed to estimate the actual reservoir rock permeability as function

Table 1.

Rock type	1 month	2 month	3 month	4 month	5 month	6 month	remark
Rigid	0	0	0	0	0	0	α=0
Elastic	40	40	40	0	0	0	α=0.005111/bar
Elastic-viscous	34	37.8	39.2	5.7	2.1	0.8	l=0.6 λ=11/month
(elastic)-plastic	40	40	40	40	40	40	η>10
Elastic-plastic-viscous	34	37.8	39.2	19.6	19.6	19.6	l=0.6 η^{**}=const=0.5

Note: well productivity is proportional with the actual (average) permeability.

of pressure load in case of rocks having complex mechanical behaviour;

- Well discharge depends on rock mechanical properties;
- Well capacity in special cases time dependent and in some cases production (injection) rate hysteresis is taken place;
- HT and HP low porosity reservoirs behave quite differently to the classical type reservoirs due to pressure load;
- Sensitivity analysis shows the importance of the research with respect to reservoir rocks having complex mechanical property.

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